Astronaut Photography: Handheld Camera Imagery from Low Earth Orbit

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Abstract

Photographic observations of the Earth by humans in low earth orbit, in contrast to unmanned orbital sensor systems, began during the 1960s as part of both the USA and former USSR manned space flight programs. The value of regularly repeated photographic observations of the Earth from orbit was demonstrated by later long-duration missions and led directly to the development of unmanned, multispectral orbital sensors such as the Multispectral Scanner and Thematic Mapper onboard the Landsat series of satellites. Handheld imagery of the Earth has been continually acquired during both USA and USSR/Russian space station and Space Shuttle programs, and represents a rich dataset that complements both historical and current unmanned sensor data for terrestrial studies. This chapter provides an overview of astronaut/cosmonaut imagery and development of specific data collection programs, then moves on to discussion of technical aspects of both the historical film and current digital cameras used in orbit with information on how to access online datasets. Case studies are presented to highlight varied applications of handheld imagery for terrestrial research and natural hazard response. The chapter concludes with discussion of future directions for digital handheld imagery of the Earth from manned orbital platforms such as the International Space Station.

Keywords

Apollo • Astronaut • Atmospheric science • Camera • Cosmonaut • Ecology • Film • Geography • Geology • Hazards • Human space flight • Hydrology • International space station (ISS) • Meteorology • Mir • National aeronautics and space administration (NASA) • Oceanography • Skylab • Space shuttle • Urban

Introduction

Remote sensing – the detection of surface-material properties such as composition and texture without physical interaction with the material – is an important analytical approach for investigating and monitoring planetary surface processes. For many Earth scientists, remotely sensed data is strongly associated with unmanned satellites. Remotely sensed data typically is collected by automated sensors on satellites in high polar and sun-synchronous orbits at approximately 700–900 km altitude above the earth's surface. Following the advent of civilian, government-supported orbital platforms in 1972 (e.g., Landsat) remotely sensed data has become an important resource for Earth scientists.

There is another spatially and temporally extensive remotely sensed dataset available for terrestrial studies and applications: systematic photographic images

of the earth taken by astronauts from the NASA Mercury missions of the 1960s to the present International Space Station (ISS) crews. The astronaut photography dataset covers much of the earth's land and coastal surface, as well as atmospheric phenomena such as hurricanes and aurora. Unlike the unmanned satellite-based sensors mentioned above, astronauts use off-the-shelf film and digital cameras to image the earth, rather than mission-specific instruments. Such equipment limits astronaut photographs to the visible and near-infrared wavelengths in three bands (red, green, blue, and/or near-infrared with appropriate filters and films), similar to what is collected by aerial photograph surveys. The majority of astronaut photographs were taken from altitudes of 300–400 km (185–250 miles) – the most notable exception being the Apollo missions to the Moon during 1969–1972. Currently the ISS is the primary manned platform for astronaut photography, which is acquired exclusively with digital cameras.

Today, the process of acquiring high-quality and scientifically useful images of the earth begins with astronaut training in the Earth Sciences. This training is provided for ISS crews by the Crew Earth Observations (CEO) team at the NASA Johnson Space Center in Houston, Texas (Stefanov 2008). Experts in a variety of disciplines provide ISS crewmembers with the science background appropriate to a variety of research image foci including glaciers, urban areas, long-term ecological monitoring sites, volcanoes, aurora, coral reefs, and deltas (both coastal and inland). This training provides the astronaut with the scientific context of a given image request. Experience with numerous crew members over the years indicates that intellectually engaged crew members tend to take higher quality data.

Collection of digital imagery from manned space vehicles such as the Space Shuttle and ISS is request-driven, with specific operational procedures and constraints. Each day CEO personnel examine the predicted ISS orbital path for the coming 24 h to determine which science targets may be visible to the crew. This list is then filtered by predicted cloud cover and illumination conditions, daily crew schedule, and the ISS ground track relative to the target's latitude/longitude position. The resulting target list is then augmented with additional instructions and data – such as landmark features to aid in locating a target, desired camera focal lens, additional imagery, etc. – and uplinked to the ISS crew. Returned imagery of targets is routinely reviewed to determine whether imagery objectives have been met. The ability to request targets of opportunity, such as volcanic eruptions and hurricanes, adds a near-real-time response capability to the ISS for hazard detection and management.

Historical Overview of Astronaut Photography

USA Space Program

Observing the Earth from space is one of NASA's longest-standing science experiments. For nearly 50 years, US astronauts have trained for and performed

observations of the Earth from orbiting spacecraft, starting with the Mercury missions and continuing today on the International Space Station. The legacy of NASA's Astronaut Earth Observations program is evident in the wealth of Earth observation data now available to the global citizenry. Viewing the Earth from space is now routine and fully integrated into our daily habits due to widespread Internet access, advances in both data visualization and serving technologies, and ready availability of sophisticated personal computing devices such as laptops, tablets, and smart phones.

Since the beginning of the US human spaceflight programs in the early 1960s, a broad community of scientists has been involved in defining Earth observations objectives and training crew members about Earth processes. Support for Earth observations increased rapidly during the 1960s to support development of new unmanned sensors, and was reinforced by the intensive geological training for the future Apollo program. Other authors have written extensively about these early programs, e.g., Amsbury (1989) and references therein; (Compton et al. 1989; Wilhelms 1993).

Handheld photography from space started in the Mercury program when payload volume expanded to include cameras and film for photographing the Earth. Structured crew Earth observations developed quickly during the Gemini program, and resulted in dedicated experiments to develop systematic capabilities. The new views of the Earth from space excited both the public and scientists, and were published in several technical reports (Anonymous 1968; Derr et al. 1972; Ewing et al. 1965; Foster 1967; Foster and Smistad 1967; Gill 1967; Lowman 1965, 1969b) and popular venues, e.g., Lowman (1966a). The early Apollo test flights were used to evaluate specific imagery applications (stereo photography, documentation of changes, weather photography) and also functioned as a test bed for demonstrating the capabilities of different films (color infrared and filtered multispectral grayscale) for future multispectral sensors on satellites, such as the US Landsat program (Amsbury 1989; Kaltenbach 1970; NASA 1970a). During this time the astronauts worked closely with investigators to obtain the best images for these projects, demonstrating the success of interactive teams of scientists and astronauts.

By the mid-1960s, crews were actively engaged in geology training in key locations in the western USA. Even as the training for future lunar missions accelerated, NASA maintained support for crew Earth observations to support ongoing scientific investigations. Crew Earth observations peaked during the Skylab missions, supporting the highly successful Earth Resources Experiment Program (EREP). EREP involved scores of scientists who selected sites, conducted field studies, trained the crews, and analyzed the orbital data (NASA 1974b, 1977). A fuller account of the early Earth observations training programs and additional references is contained in (Amsbury 1989).

The Skylab EREP program was succeeded by the Space Shuttle Earth Observations Program (SSEOP), established in the early 1980s. The early activities of the office supporting this program are described in (Helfert and Wood 1989). Astronaut training in the Earth Sciences was a prime function, with the goal of providing

critical scientific background to the crews to enable the acquisition of scientifically meaningful astronaut photography. The office staff included scientists from several disciplines in the Earth Sciences (meteorology, geology, oceanography, ecology, and geomorphology); they trained the crews, evaluated target requests, and planned and coordinated observation campaigns for each flight. Throughout the 1980s and 1990s, the SSEOP obtained a broad set of medium-resolution imagery using a variety of medium and large format cameras that complemented data from the unmanned Earth observations satellites of the time. Some flights supported specific data collection campaigns such as the Shuttle Imaging Radar missions (Cimino et al. 1986; Elachi et al. 1982; Evans et al. 1997) and the LIDAR In-space Technology Experiment, or LITE (Winker et al. 1996). Science targets and associated equipment (cameras, lenses, film complement) were selected based on the mission's orbit tracks, projected lighting, season, spacecraft altitude, and current events. Staff scientists provided last-minute updates to the crew a few days before flight, such as overviews of weather systems and noteworthy events (e.g., volcanic activity, biomass burning locations, tropical storms, and floods). During flight, the science team on the ground communicated with the crew daily about upcoming sites, global weather patterns, and additional targets based on current events.

The Shuttle-Mir program in the mid-1990s, followed by early missions to the ISS in 2000, allowed NASA's Earth scientists' insight into differences between shorter Space Shuttle flights and longer duration missions on a space station in terms of observational styles and appropriate scientific targets. In contrast to the SSEOP science strategy, based on the spaceflight parameters of short (less than 2 week duration) Space Shuttle missions and built around specifics of each flight (time of launch, season, mission objective, basic spacecraft attitude relative to Earth, orbital parameters including inclination and altitude), a modified scientific approach was adopted for astronauts and cosmonauts flying long-duration missions to the Russian Mir Space Station from 1996 to 1998. Building from both the Shuttle experience and Russian Earth Science approach (Glazovskiy and Dessinov 2000), the Shuttle-Mir Earth Observations strategy adjusted for the set orbital inclination, the changing views with seasonal shifts and changing solar illumination (Mir, like the current ISS, was not sun-synchronous). The Shuttle-Mir program segued directly to the current CEO program described above.

Over time, the ISS CEO program has increasingly favored an interdisciplinary Earth Science approach, integrating other remotely sensed data and new emphasis on coastal processes, human footprints, and environmental change into both crew training and target selection. Astronauts from ISS partner organizations, such as the Canadian Space Agency and European Space Agency, are occasionally trained in Earth observations as part of the CEO program as well. Recent NASA planning for potential return missions to the Moon, Mars, or Near-Earth Objects has revived more intensive geological and remote sensing training for incoming astronaut-candidate classes based in part on the Apollo-era training program, with the expectation of additional benefits to Earth observations (Evans et al. 2011).

USSR/Russian Space Program

The history of the Soviet Earth observations program during the early years (1960s) mirrored the US Earth Observations program, starting with Yuri Gagarin's flight in 1961. In the beginning much of the cosmonaut photography of the Earth was initiated by cosmonaut interest, rather than a systematic program-level approach. The early cosmonauts, using binoculars and handheld cameras, identified the potential for global, real-time observations of the planet (including dynamic events); general characterization of the Earth's surface from orbit, particularly study of geographically inaccessible regions; and the potential for comparative studies across different regions.

Glazovskiy and Dessinov (Glazovskiy and Dessinov 2000) detail the evolution of the cosmonaut-based Earth observations program in the Soviet space program through the 1960s, 1970s, and 1980s. The Earth Observations program structure was established by 1974 to support the Salyut 3–5 missions. The program was designed in collaboration with geographers at the Academy of Sciences, the Chief of Cosmonauts, the Soviet Air Force, and the RSC-Energia engineers and film experts. The cosmonauts were trained in the Earth Sciences and conducted experiments with powerful tracking binoculars equipped with cameras. Technologies and procedures were developed, including improvised motion tracking using attitude control mechanisms on the spacecraft. The capability for larger payloads enabled the use of large format cameras (e.g., KATE-140 with an 18 × 18 cm film format and longer lenses) complemented by conventional 35 mm and medium format cameras. Soviet scientists collaborated with scientists and engineers in the German Democratic Republic to develop the program and equip the spacecraft with camera systems.

The USSR Earth observations scientific program ramped up between 1977 and 1985 to support the long-duration missions on the Salyut 6 and 7 space stations. The program collaborated with dozens of institutions, and included extensive cosmonaut training in state-of-the-art facilities at the Gagarin Training Center outside of Moscow. Earth observation training flights in Tupolev-134 aircraft employed a strategy that involved close work between cosmonauts and scientists. Cosmonauts on the first Salyut 6 mission were tasked with building and refining the Earth observations procedures and testing the equipment, including fixed high-resolution nadir-looking cameras (KATE-140 and MKF-6 M cameras), powerful binoculars, and handheld cameras. The cosmonaut crews were actively involved in calculating manual controls for motion tracking by maintaining spacecraft attitude with thrusters as a means of damping out the relative ground motion. Through this method, they collected high-resolution photography of designated earth targets. During these early space station missions, cosmonauts started observing ephemeral features and events on the Earth's surface, conducted studies on changes in human visual acuity in space, and conducted simultaneous observations with aircraft surveys.

The Mir program followed in 1986, lasting through the last mission in 2000. The Earth observations program on Mir followed the strategy developed for the Salyut program, although financial support for scientists and equipment dropped during

the collapse of the USSR and the following difficult economic times lasting through the mid-1990s. The Earth observing assets on the Mir included the KATE and MKF-6 M fixed cameras, conventional handheld cameras, medium format cameras, and a variety of films including a unique color infrared film. The Priroda module, a dedicated Earth Resources facility, was launched to the Mir Station in 1996 with an international complement of remote sensing equipment. However, heavy power constraints precluded full operations of many of the Priroda instruments, and the capabilities were not realized.

Cosmonaut crews on the International Space Station are currently performing a variety of Earth observations tasks and experiments, including the "Uragan" program that began in 2001 (I. Sorokin, S.P. Korolev, 2010, personal communication). This program is similar in many ways to the early NASA Apollo and Skylab EREP programs, in that it uses digital still cameras to optimize design and test of multispectral sensor configurations for monitoring and forecast of land surface processes and hazards from space.

Specifications of Astronaut Photography

Handheld Earth imagery has been acquired by a variety of film and digital cameras over the past 50 years, from both short- and long-duration missions of spacecraft in low earth orbit. We focus our overview of astronaut photography specifications on NASA missions, spacecraft, and equipment due to the availability of extensive and accessible documentation. A discussion of USSR/Russian handheld photographic equipment up to 2000 is presented in Glazovskiy and Dessinov (2000).

In contrast to purpose-built and mission-specific multispectral and hyperspectral imaging systems for airborne and orbital platforms, the majority of cameras, binoculars, etc. used for handheld astronaut Earth photography has been commercial off-the-shelf equipment that has seen little or no modification prior to launch and on-orbit use. Cameras or imagers meant for use during extravehicular activities (e.g., Apollo and ISS astronaut suit cameras) were modified both for space hardening – reduced outgassing and operation in the vacuum and hard radiation environments – and for the operational challenges posed by space suit design and ergonomics, e.g., operating the camera with pressurized suit gloves in low or zero gravity. A full discussion of lunar orbital and surface astronaut photography, training, and equipment is outside the scope of this chapter, but the interested reader is directed to Jones et al. (2010) and Woods (2009) for more information.

Cameras, Film, and Digital Media

Film cameras have been used in all of the NASA historical and current manned spaceflight programs, including on the Space Shuttle and International Space Station, with a variety of film types used for Earth observations (Tables 28.1–28.6). The Astronaut Office, Orbiter Photo/TV Working Group, and the SSEOP, in

Table 28.1 Specifications of handheld earth observations equipment and activities during the NASA Mercury program

Mission (dates flown)	Camera/lenses/other equipment	Films/filters	Binoculars, minoculars, spotting scopes	Television	Tape recorders	Experiments	Comments	References
Mercury 3 (5 May 1961)	Maurer model 220 G 70 mm camera (fixed camera system)	Super Anscochrome	None	None	None	General information photography	More than 150 photographs taken of sky, clouds, and ocean	Lowman (1964, 1965, 1966a, b), Short and Lowman (1973), Swenson et al. (1966), Underwood (1968)
Mercury 4 (21 July 1961)	Mauer model 220 G 70 mm camera (fixed camera system)	Super Anscochrome	None	None	None	General information photography	Photography taken over the Atlantic Ocean, North and Central Africa	Grimwood (1963), Lowman (1964, 1965, 1966a, b), Short and Lowman (1973), Swenson et al. (1966), Underwood (1968)
Mercury 6 (20 February 1962)	Ansco Autoset 35 mm camera/ 55 mm lens	Eastman color negative type 5250	None	None	None	General information photography of Earth, meteorological photography planned	48 photographs taken of clouds, oceans, northwest Africa	Cortright (1968), Grimwood (1963), Kuehnel (1972), Lowman (1964, 1965, 1966a, b), Short and Lowman (1973), Swenson et al. (1966), Underwood (1968)
Mercury 7 (24 May 1962)	Robot recorder 35 mm camera	Eastman color negative type 5250	None	None	None	Photograph selected areas for terrain	155 photographs taken of Earth and Earth's limb	Cortright (1968), Grimwood (1963), Kuehnel (1972), Lowman (1964, 1965, 1966a, b), Short and Lowman (1973), Swenson et al. (1966), Underwood (1968)
Mercury 8 (3 October 1962)	Hasselblad 500C 70 mm camera (NASA modified)/ Zeiss 80 mm planar f/ 2.8 lens	Super Anscochrome	None	None	None	Synoptic terrain photography experiment	Photography obtained of poor quality due to general overexposure	Grimwood (1963), Kuehnel (1972), Lowman (1964, 1965, 1966a, b), Short and Lowman (1973), Swenson et al. (1966), Underwood (1968)
Mercury 9 (15–16 May 1963)	Same as Mercury 8	Ultraspeed Anscochrome (fpc-289)	None	None	None	Same as Mercury 8	29 photographs taken of Earth and cloud features, including observations on visibility and color of Earth features	Cortright (1968), Grimwood (1963), Kuehnel (1972), Lowman (1964, 1965, 1966a, b), Short and Lowman (1973), Swenson et al. (1966), Underwood (1968)

Table 28.2 Specifications of handheld earth observations equipment and activities during the NASA Gemini program

Mission (dates flown)	Camera/lenses/other equipment	Films/Filters	Binoculars, minoculars, spotting scopes	Television	Tape recorders	Experiments	Comments	References
Gemini 3 (23 March 1965)	Hasselblad 500C 70 mm camera (NASA modified)/Zeiss 80 mm planar f/2.8 lens	70 mm, Ektachrome MS SO-217/Haze filter	None	None	None	General terrain and meteorology information photography	219 Earth-looking photographs taken	Carter and Stone (1974), Giddings (1975), Grimwood (1969), Kuehnel (1972), Lowman (1966a, 1968), Lowman and Tiedemann (1971), NASA (1966, 1967a, b), Short and Lowman (1973), Underwood (1968)
Gemini 4 (3–7 June 1965)	Hasselblad 500C 70 mm camera (NASA modified)/Zeiss planer 80 mm f/2.8 lens	70 mm Ektachrome MS SO-217 and 3401	None	None	None	Synoptic terrain photography experiment S005, Synoptic weather photography experiment S006	219 Earth-looking photographs taken	Badgley et al. (1969), Carter and Stone (1974), Cortright (1968), Giddings (1975), Grimwood (1969), Kuehnel (1972), Lowman (1966a, 1968, 1972), Lowman and Tiedemann (1971), Lowman et al. (1967), NASA (1966, 1967a, b, c), Short and Lowman (1973), Stevenson et al. (1968), Underwood (1968), Wobber (1968), Zeitler et al. (1971)
	Zeiss Contarex 35 mm camera/250 mm lens	Anscochrome D-200 film/Haze filter						
	Maurer 16 mm motion picture camera	Ektachrome film						

(*continued*)

Table 28.2 (continued)

Mission (dates flown)	Camera/lenses/other equipment	Films/Filters	Binoculars, minoculars, spotting scopes	Television	Tape recorders	Experiments	Comments	References
Gemini 5 (21–29 August 1965)	Hasselblad 500C 70 mm camera (NASA modified)/Zeiss planer 80 mm f/2.8 lens	70 mm Ektachrome MS SO-217 and 3401	None	None	None	Same as Gemini 4, with visual acuity experiment S008, Surface photography experiment D006	250 Earth-looking photographs taken	Carter and Stone (1974), Cortright (1968), Giddings (1975), Grimwood (1969), Kuehnel (1972), Lowman (1966a, 1968, 1972), Lowman and Tiedemann (1971), NASA (1966, 1967a, b, c), Pesce (1968), Short and Lowman (1973), Stevenson et al. (1968), Underwood (1968), Wobber (1968), Zeitler et al. (1971)
	Zeiss Contarex 35 mm camera/250 mm lens, 1,200 mm Questar lens	Anscochrome D-50 and D-200/ Haze filter						
	Maurer 16 mm motion picture camera with spotmeter	Ektachrome film						
Gemini 6-A (15–16 December 1965)	Hasselblad 500C 70 mm camera (NASA modified)/Zeiss planer 80 mm f/2.8 lens	70 mm Ektachrome MS SO-217 and type 2475/Haze filter	None	None	None	Same as Gemini 4	192 Earth-looking photographs taken	Carter and Stone (1974), Cortright (1968), Giddings (1975), Grimwood (1969), Kuehnel (1972), Lowman (1966a, 1968, 1972), Lowman and Tiedemann (1971), NASA (1966, 1967a, b, 1968d), Short and Lowman (1973), Underwood (1968), Wobber (1968), Zeitler et al. (1971)
	Maurer 16 mm motion picture camera with spotmeter	Ektachrome film						

Gemini 7 (15–16 December 1965)	Hasselblad 500C (NASA modified)/Zeiss planar 80 mm f/2.8 lens	70 mm Ektachrome MS SO-217 and Ektachrome infrared 8443	None	None	None	Experiment S005, S006, S008. Landmark contrast measurement experiment M412	429 Earth-looking photographs taken	Carter and Stone (1974), Cortright (1968), Giddings (1975), Grimwood (1969), Kuehnel (1972), Lowman (1966a, 1968, 1972), Lowman and Tiedemann (1971), NASA (1966, 1967a, b, 1968d), Pesce (1968), Short and Lowman (1973), Underwood (1968), Stevenson et al. (1968), Wobber (1968), Zeitler et al. (1971)
	Zeiss Contarex 35 mm camera/250 mm lens	Panatomic X 3400 and type 2475/ Haze filter						
	Maurer 16 mm motion picture camera with spotmeter	Ektachrome film						
Gemini 8 (16 March 1966)	Hasselblad 500C (NASA modified)/Zeiss planar 80 mm f/2.8 lens	70 mm Ektachrome MS SO-217/Haze filter	None	None	None	General Terrain and meteorology information photography	19 photographs taken, one of Earth's limb, six Earth-looking oblique photographs	Carter and Stone (1974), Cortright (1968), Grimwood (1969), Kuehnel (1972), NASA (1967a, 1968d), Short and Lowman (1973), Underwood (1968)
	Maurer 16 mm motion picture camera with spotmeter	Ektachrome film for Maurer cameras						
	Maurer 16 mm motion picture camera							
Gemini 9-A (6 June 1966)	Hasselblad 500C (NASA modified)/Zeiss planar 80 mm f/2.8 lens	70 mm Ektachrome MS SO-217/Haze filter	None	None	None	Same as Gemini 8	362 Earth-looking photographs taken	Cortright (1968), Giddings (1975), Grimwood (1969), Kuehnel (1972), Lowman (1968), Lowman and Tiedemann (1971), NASA (1967a, 1968d), Short and Lowman (1973), Stevenson et al. (1968), Underwood (1968), Zeitler et al. (1971)
	Hasselblad super wide angle-C (NASA modified)/Zeiss Biogon 38 mm, f/4.5 lens							
	Maurer 70 mm Space Camera/Xenotar 80 mm f/2.8 lens							
	Maurer 16 mm motion picture camera with spotmeter	Ektachrome film						

(*continued*)

Table 28.2 (continued)

Mission (dates flown)	Camera/lenses/other equipment	Films/Filters	Binoculars, minoculars, spotting scopes	Television	Tape recorders	Experiments	Comments	References
Gemini 10 (18–21 July 1966)	Hasselblad super wide angle/Zeiss Biogon 38 mm, f/4.5 lens Maurer 70 mm Space Camera/Xenotar 80 mm, f/2.8 lens Maurer 16 mm motion picture camera with spotmeter	Same as Gemini 9-A	None	None	None	Experiments S005, S006, M412. Color patch photography experiment M410	371 Earth-looking photographs taken	Carter and Stone (1974), Cortright (1968), Giddings (1975), Grimwood (1969), Kuehnel (1972), Lowman (1968), Lowman and Tiedemann (1971), NASA (1967a, b, 1968d), Short and Lowman (1973), Stevenson et al. (1968), Underwood (1968), Zeitler et al. (1971)
Gemini 11 (12–15 Sep 1966)	Hasselblad super wide angle/Zeiss biogon 38 mm, f/4.5 lens Maurer 70 mm space camera/Xenotar 80 mm, f/2.8 lens Maurer 16 mm motion picture camera with spotmeter	70 mm Ektachrome MS SO-368 film/Haze filter Ektachrome film	None	None	None	Experiments S005, S006	238 Earth-looking photographs taken	Carter and Stone (1974), Cortright (1968), Giddings (1975), Grimwood (1969), Kuehnel (1972), Lowman (1968), Lowman and Tiedemann (1971), NASA (1967a, 1968d), Short and Lowman (1973), Stevenson et al. (1968), Underwood (1968), Zeitler et al. (1971)
Gemini 12 (11–15 Nov 1966)	Same as Gemini 11	Same as Gemini 11	None	None	None	Experiments S005, S006 and ocean features photography	415 Earth-looking photographs taken	Carter and Stone (1974), Cortright (1968), Giddings (1975), Grimwood (1969), Kuehnel (1972), Lowman (1968), Lowman and Tiedemann (1971), NASA (1967a, b, 1968d), Short and Lowman (1973), Underwood (1968), Stevenson et al. (1968), Wobber (1968), Zeitler et al. (1971)

Table 28.3 Specifications of handheld earth observations equipment and activities during the Apollo program

Mission (dates flown)	Camera/lenses/other equipment	Films/filters	Binoculars, minoculars, spotting scopes	Television	Tape recorders	Experiments	Comments	References
Apollo 4 (9 Nov 1967)	Maurer Model 220 G 70 mm Sequence camera/ Ektar 76 mm f/2.8 lens (exposure setting 1/500 of a second)	70 mm Ektachrome MS So-368	None	None	None	Acquisition and return of highest altitude photography (~18,520 km) taken of Earth	712 photographs of Earth (2,136 Earth-looking photographs taken with the 70 mm camera during the Apollo 4, 6, 7, 8, 9, 10, 11 and 12 missions)	Dornbach (1968), Underwood (1968)
Apollo 6 (4 Apr 1968)	Maurer Model 220 G 70 mm sequence camera/ Ektar 76 mm f/2.8 lens	Same as Apollo 4	None	None	None	To obtain sequenced vertical photographs of Earth in stereo	Vertical or near-vertical photographs of Earth between ~183 and 306 km altitude. 372 Earth-looking photographs taken	Amsbury et al. (1969), Badgley et al. (1969), Dornbach (1968), Kaltenbach et al. (1969a), Lowman (1972), NASA (1968a, b, 1970b), Short and Lowman (1973)
Apollo 7 (11–22 Oct 1968)	Hasselblad model 500 C (NASA modified)/Zeiss planar 80 mm f/2.8 lens Maurer 16 mm sequence cam-Era/75 mm lens	70 mm Ektachrome MS SO-368, SO-121, and B&W type 3400/ Wratten 2A, 25A (red) and 58 (green) filters used with SO-121 film	Leitz monocular telescope (10X magnification, objective diameter 40 mm)	TV equipment, hand held or mounted. (Black & White)	Data tape recorder. Speed 9.5, 38, 305 cm/s, Tape 686 m	Synoptic terrain photography experiment S005, Synoptic weather photography experiment S006	Photographs taken of Earth between ~159 and 367 km altitude. 502 Earth-looking photographs taken. Hardware training for general photography and experiments given for each Apollo Mission	Amsbury et al. (1969), Carter and Stone (1974), Kaltenbach et al. (1969b), Kuehnel (1972), NASA (1968c, 1969a, 1970b, 1973a), Short and Lowman (1973)

(*continued*)

Table 28.3 (continued)

Mission (dates flown)	Camera/lenses/other equipment	Films/filters	Binoculars, minoculars, spotting scopes	Television	Tape recorders	Experiments	Comments	References
Apollo 9 (3–13 Mar 1969)	Hasselblad model 500EL (NASA modified)/Zeiss planar 80 mm f/2.8 lens	70 mm Ek- tachrome MS SO-368/Haze filter	Same as Apollo 7	Same as Apollo 7 (first color TV flown on Apollo 10)	Same as Apollo 7	Multispectral photography experiment SO65. Terrain, weather, air glow, and Earth's limb sites of opportunity were planned	127 vertical or near-vertical photographs taken of Earth in each of the four bands of the SO65 Experiment. 1,157 Earth-looking photographs taken with the handheld Hasselblad 70 mm camera. (A number of excellent 70 mm handheld color photographs were taken of the Earth during Earth orbit and enroute to and from the Moon on the Apollo 8, 10, 11, 12, 13, 14, 15, 16, and 17 missions)	Amsbury et al. (1969), Badgley et al. (1969), Bannert (1972), Carter and Stone (1974), Kaltenbach (1970), Kuehnel (1972), Lowman (1969a, 1972), NASA (1969b, c, 1970b, 1973a), Nicks (1970), Schowengerdt and Slater (1972), Short and Lowman (1973)
	SO65 Experiment: Hasselblad Model 500EL/ Zeiss planar 80 mm, f/2.8 lens/Photar 15 filter	70 mm Ektachrome IR, SO-180						
	Hasselblad Model 500EL/ Zeiss planar 80 mm f/2.8 lens/Photar 58B filter	70 mm B&W Panatomic X, type 3400						
	Hasselblad Model 500EL/ Zeiss planar 80 mm, f/2.8 lens/Photar 89B filter	70 mm B&W Infrared SO-246						
	Hasselblad Model 500EL/ Zeiss Planar 80 mm, f/2.8 lens/Photar 25A filter	70 mm B&W Panatomic X, type 3400						
	Maurer 16 mm data acquisition camera (DAC)/ 75 mm lens	Ektachrome SO-368 for Maurer DAC						

Table 28.4 Specifications of handheld Earth observations equipment and activities during the Skylab program

Mission (dates flown)	Camera/lenses/other equipment	Films/filters	Binoculars, minoculars, spotting scopes	Television	Tape recorders	Experiments	Comments	References
Skylab 2 (25 May to 22 June, 1973)	Multispectral photographic facility (MPF, s190): Multispectral photographic camera (S190A). Six Itek 70 mm boresighted cameras/ high precision f/2.8, 21.2 degree FOV lenses	MPF: 70 mm film: Station1-IR B & W (0.7–0.8 μm)	Leitz Trinovid 10 × 40 binoculars (space modified)	Westing house color 25–150 mm zoom. Focus range 20″ to infinity	Same as Apollo 7	Obtain data with the Earth resources experiment package (EREP) sensors. Obtain general information photography of Earth	35,000 frames cycled through S190A during Skylab 2, 3, and 4. (Not all of these were exposed or Earth-looking)	Kaltenbach et al. (1974), Kenney (1974, 1975), Lockwood and Sauer (1975), Lowman et al. (1973), Mcniel and Devalcourt (1974a), NASA (1973a, b, 1974b), Stevenson (1974), Underwood and Holland (1973a)
		Station 2-IR B & W (0.8–0.9 μm)			Video tape recorder, recording time 30 min			
		Station 3 Aerochrome IR color type EK2243 (0.5–0.88 μm)					32,994 Earth-looking photographs taken with S190A and 5,569 Earth-looking photographs taken with S190B during Skylab 2,3,and 4	
		Station 4- color SO-356 (0.4–0.7 μm)						
		Station 5- Panatomic-X B & W SO-022 (0.6–0.7 μm)					302 Earth-looking photographs taken with the handheld Hasselblad 70 mm camera, and 355 Earth-looking photographs taken with the handheld Nikon 35 mm cameras	
		Station 6- Panatomic-X B & W SO-022 (0.5–0.6 μm)						

(*continued*)

Table 28.4 (continued)

Mission (dates flown)	Camera/lenses/other equipment	Films/filters	Binoculars, minoculars, spotting scopes	Television	Tape recorders	Experiments	Comments	References
Skylab 2 (25 May to 22 June, 1973)	Actron Earth Terrain Camera (AETC, S190B)/Five inch format, f/4 lens, 18 inch focal length 16 mm DAC boresighted on Visual tracking system infrared spectrometer (S191) field of view	AETC: color SO-242 (0.4–0.7 μm) B & W EK3414 (0.5–0.7 μm) Ektachrome SO368					A number of Earth-looking TV passes were performed Note: The S190A, S190B and S191 are instruments in the Earth Resources Experiment Package (EREP) which obtained information of the Earth in numerous spectral regions during the three manned Skylab flights.	Kaltenbach et al. (1974), Kenney (1974, 1975), Lockwood and Sauer (1975), Lowman et al. (1973), Mcniel and Devalcourt (1974a), NASA (1973a, b, 1974b), Stevenson (1974), Underwood and Holland (1973a)
	Hasselblad Model 500EL (electric data camera system with Reseau plate), 70 mm camera/100 mm lens	70 mm Ektachrome SO-368						
	Nikon 35 mm Cameras (5)/ 55 mm and 300 mm lenses	Ektachrome SO-368, SO-168, 2485 and 2443 type						
	Maurer 16 mm DAC/5, 10, 18, 25, 75, & 100 mm lenses	Ektachrome SO-368 and SO-168						
Skylab 3 (28 July to 25 Sep 1973)	S190A, S190B, Hasselblad, Nikon, and DAC's same as Skylab 2	S190A, Hasselblad, Nikon, and DAC's film and filters same as Skylab 2	Same as Skylab 2	Same as Skylab 2	Same as Skylab 2	Obtain data with the Earth resources Experiment package (EREP) sensors.	642 Earth-looking photographs taken with the handheld Hasselblad 70 mm camera, and 537 Earth-looking photographs taken with the handheld Nikon 35 mm cameras.	Kaltenbach et al. (1974), Kenney (1974, 1975), Lockwood and Sauer (1975), Lowman et al. (1973), Mcniel and Devalcourt (1974b), NASA (1973a, b, 1974b), Stevenson (1974), Underwood and Holland (1973b)
						Obtain general information photography of Earth.		
	Earth Terrain Camera (S190B)	SO-242 (0.4–0.7 μm)						
		EK3414 (0.5–0.7 μm)					A number of Earth-looking TV passes were performed	
		Infrared color EK3443 (0.5–0.88 μm)						

Skylab 4 (16 Nov 1973 to 8 Feb 1974)	S190A, S190B, Hasselblad, Nikon, and DAC's same as Skylab 2 & 3	S190A, Hasselblad, Nikon, and DAC's film and filters same as Skylab 2 & 3	Leitz Trinovid 10 × 40 binoculars (Space modified)	Same as Skylab 2	Same as Skylab 2	Obtain data with the Earth resources Experiment package (EREP) sensors. Obtain general information photography of Earth	1,260 Earth-looking photographs taken with the handheld Hasselblad 70 mm camera, and 1,255 Earth-looking photographs taken with the handheld Nikon 35 mm cameras	Kaltenbach et al. (1974), Kenney et al. (1974, 1975), Lockwood and Sauer (1975), Lowman et al. (1973), NASA (1973a, b, 1974b), Stevenson (1974), Underwood and Holland (1974)
	Earth Terrain Camera (S190B)	SO-242 (0.4–0.7 μm)					A number of Earth-looking TV passes were performed	
		EK3414 (0.5–0.7 μm)						
		Infrared color (high resolution) EK3443 (0.5–0.88 μm)						

Table 28.5 Specifications of handheld Earth observations equipment and activities during the Apollo–Soyuz project

Mission (dates flown)	Camera/lenses/other equipment	Films/filters	Binoculars, minoculars, spotting scopes	Television	Tape recorders	Experiments	Comments	References
Apollo-Soyuz Test Project (15–24 Jul 1975)	Two 70 mm Hasselblad Model 500EL Cameras: One reflex camera with 50 mm and 250 mm lenses	SO-242/Wratten 2A; SO-368 (QX807)/film coated with equivalent of Wratten 2A	Leitz Trinovid 10 × 40 Binoculars (Space modified)	ASTP Television System (camera, lens, monitor)	Modified Sony Cassette-Coder Model TC-SS for voice recorder and playback	Earth Observations and photography Experiment MA-136	1,916 Earth-looking photographs taken; 751 good exposures obtained	NASA (1974a, 1977, 1976)
	One electric Data Camera System with Reseau plate with 60 mm and 100 mm lenses	Infrared color, Type 2443 equivalent/ Wratten 12		Operated in Apollo and Soyuz. Zoom 6–1 and 3–1.	Video tape recorder recording time 30 min. Data tape recorder same as Skylab 2		A number of Earth-looking TV passes were performed	
	One 35 mm Nikon camera/35 mm lens (interior photography), 300 mm lens (exterior photography)	Ektachrome		Range 25–150 mm, 9–27 mm. F-stop 4.4–44, 3.5–35				
	16 mm Data Acquisition Camera/ 10 mm, 25 mm, and 75 mm lenses	Ektachrome		Focus 51 cm-inf., 30.5 cm - inf. (modified Westinghouse)				
	Spotmeter							

conjunction with the JSC photo lab, Kodak, and camera hardware vendors conducted a variety of tests on various film and hardware combinations, with the end goal of producing the highest resolution images with the greatest dynamic range and the best color reproduction, and minimized image artifacts (e.g., film graininess or image vignetting). The tests were driven by factors that included market and environmental considerations (film production and streamlined film

Table 28.6 Specifications of handheld Earth observations film cameras and films used during the Space Shuttle and ISS programs

Cameras	Lenses	Film types
Hasselblad 500 EL/M, 70 mm, NASA modified	Zeiss 40 mm	Fuji, natural color positive, Velvia 50, CS-135-36, ASA 32, standard base
	Zeiss 50 mm	
	Zeiss 80 mm	
	Zeiss 100 mm	Kodak
	Zeiss 110 mm	B & W, Plus-X Aerographic
	Zeiss 250 mm	Color negative, Vericolor III, 70 mm unperforated, process C-41
	Zeiss 350 mm	
		Natural color positive, Ektachrome Professional 5017, ASA 64, standard base
		Natural color positive, Ektachrome 5036, 200 Professional, ASA 200, standard base
		Natural color positive, Ektachrome Professional SO-117, ASA 400, standard base
		Natural color positive, Lumiere 100/5046, ASA 100, standard base
		Natural color positive, Lumiere 100×/5048, ASA 100×, standard base
		Natural color positive, Ektachrome MS, ASA64, thin base, fine grain
		Color positive, Ektachrome X Professional, ASA 64, standard base
		Color positive, Ektachrome SO-368, fine grained, with yellow dye layer equivalent to Wratten 2A
		Color positive, Ektachrome, high speed, ASA 400
		Color positive, Ektachrome 64, 220 Roll format
		Color positive, Ektachrome 64
		Color positive, Aerochrome II color-reversal, ISO-A 32, , process EA-5, standard base
		Color positive, Elite 100 S, E6 reversal
		Color infrared, Aerochrome 2443, ASA 160, standard base
		Russian color infrared, 2 dye layer, estimated ASA 64

(*continued*)

Table 28.6 (continued)

Cameras	Lenses	Film types
Linhof Aero Technika, 100 × 120 mm, NASA modified	Linhof 90 mm	Kodak
	Linhof 250 mm	Natural color positive, Ektachrome QX 868, ASA 64, 5017 emulsion, thin base
		Natural color positive, Lumiere 100/5046, ASA 100, standard base
		Natural color positive, Lumiere 100×/5048, ASA 100×, standard base
		Color positive, Elite 100 S, E6 reversal
		Color positive, Ektachrome X Professional, ASA 64, standard base
		Color positive, Ektachrome 64, 220 roll format
		Color positive, Aerochrome II color-reversal, ISO-A 32, standard base
		Color positive, Aerochrome II Duplicating Film, 70 mm, process EA-5
		Color infrared, Aerochrome 2443, EA-5 process through June 1999, E-6 process afterward, thin base
Rolleiflex, 70 mm, NASA modified	Zeiss 50 mm	Kodak, natural color positive, Ektachrome Professional 5017, ASA 64, standard base
	Zeiss 80 mm	
	Zeiss 100 mm	
	Zeiss 250 mm	
Nikon F3 35 mm, NASA modified	All lenses are interchangeable and autofocus:	Fuji
		Natural color negative, NHG, ASA 400, standard base
		Color negative, 35 mm, ASA 800
Nikon F4 35 mm, NASA modified	16 mm	Natural color positive, Velvia 50, CS-135-36, ASA 32,standard base
	20 mm	Kodak
	28 mm	
	35 mm	B &W positive, Technical Pan Film 2415 Estar AH Base, ASA 100
	35–70 mm	
	zoom	Natural color negative, Ektar 100–3101, ASA 125, standard base
	55 mm	
	60 mm	Natural color negative, Ektapress 5030, ASA 1600, standard base
	70 mm	
	85 mm	Natural color negative, Vericolor III 5026, ASA 160, standard base
	180 mm	
	300 mm	Color negative, Kodacolor VRG/100, ASA 100, standard base
	400 mm	
		Color negative, Ektar 25 Professional Film, ASA 25
		Color negative, Pro 400, 35 mm, ASA 400

(*continued*)

Table 28.6 (continued)

Cameras	Lenses	Film types
Nikon F4 35 mm, NASA modified	2X doubler	Color negative, Pro PMZ 1000, 35 mm or 120 mm, process C-41
		Natural color positive, Ektachrome Professional 5017, ASA 64, standard base
		Natural color positive, Ektachrome Professional 5074, ASA 400, standard base
		Natural color positive, Ektar 25 Professional, ASA 25, standard base
		Color positive, Vericolor 400 Prof (VPH), ASA 400, standard base
		Color positive, Ektachrome X Professional, ASA 64, standard base
		Color positive, Ektachrome 64 T Professional Film, ASA 64
		Color positive, Elite 100 S, E6 reversal
		Color positive, EXR 500
		Portra
		Color negative, 160NC, 35 mm, ASA 160
		Color negative, 400NC, 35 mm, ASA 400
		Color positive, 400VC, 35 mm, ASA 400

Table 28.7 Digital SLR cameras used in the Space Shuttle and ISS programs (Nikon D2Xs, D3, D3X, and D3S cameras are currently in use onboard the ISS)

Manufacturer/model	Original image size (mm)	Original image size (pixels)
Sony HDW-700 high-definition television camcorder	–	1,920 × 1,035 interlaced
Kodak DCS460, RGBG array	27.6 × 18.5	3,060 × 2,036
Kodak DCS660, RGBG array	27.6 × 18.5	3,060 × 2,036
Kodak DCS760, RGBG array	27.6 × 18.5	3,060 × 2,036
Nikon D1, RGBG imager color filter	23.6 × 15.5	2,000 × 1,312
Nikon D2Xs, RGBG imager color filter	23.7 × 15.7	4,288 × 2,848
Nikon D3	36.0 × 23.9	4,256 × 2,832
Nikon D3X	35.9 × 24.0	6,048 × 4,032
Nikon D3S	36.0 × 23.9	4,256 × 2,832

development processes), image resolution results (for example, using faster ISO 100 films and faster lenses, enabling shorter exposure times), on-orbit operational flexibility (e.g., using auto exposures rather than calculating appropriate f-stops) and, ultimately, new digital technologies.

Both the Shuttle and ISS programs – and international partners – transitioned to exclusive use of digital 35 mm Single Lens Reflex (SLR) and video cameras in 2004 (Table 28.7). Coupled with improvements in operational uplink/downlink of

Table 28.8 Calculated ground resolutions for representative film and digital still cameras used on the International Space Station

		Ground resolution in m/pixel at image center	
		Minimum altitude = 368 km asl	Maximum altitude = 386 km asl
Camera	Lens (mm)		
Hasselblad 70 mm	110	35.4	37.1
	250	15.6	16.3
	350	11.1	11.6
Nikon 35 mm	300	13.0	13.6
	400	9.7	10.2
Kodak DSC	300	11.0	11.6
	400	8.3	8.7
	800	4.2	4.4

Altitudes are given as km above sea level (asl), and calculated resolutions do not include effective ground motion blurring caused by the high orbital velocity of the ISS (~27,500 km/h) relative to the Earth's rotation

data between ground stations and orbiting spacecraft, the use of digital cameras has both increased the volume of imagery and decreased the lag time between acquisition and public availability of data. A variety of interchangeable fixed focal length and zoom lens have also been (and continue to be) used with both the film and digital cameras, producing a wide range of ground resolutions in the handheld imagery dataset (Table 28.8).

More recently, improvements in camera technology, crew photographic technique, and improved lenses have enabled collection of images with center pixel resolutions approaching 2 m/pixel. Most handheld astronaut photography is also oblique – has a viewing angle relative to the earth surface less than 90° – to some degree which introduces varying ground resolution per pixel across a given image. For these reasons, it is difficult to assign a standard per pixel ground resolution to the astronaut photography dataset as is common with other orbital sensor datasets.

Original film negatives of handheld Earth observations imagery are archived in a cold-storage facility at the NASA Lyndon B. Johnson Space Center (JSC) in Houston, TX. Much of the historical film archive has been digitally scanned into standard formats (such as JPEG and TIFF) and is available online for review and download (see discussion below on online access to data). Many frames of Earth observation data, particularly for the early manned missions, have not been scanned in a systematic fashion however. Scanning of individual film frames of interest can be requested through the JSC Media Services Center.

Processing, Archiving, and Accessing Astronaut Photography

Digital camera imagery taken by astronauts is stored onboard the Space Shuttle or ISS and periodically transmitted to the ground using NASA or Russian downlink systems (both geosynchronous satellite network and line of sight). Handheld

camera imagery taken by NASA or partner agency astronauts, whether on physical film rolls or downlinked digital files, is initially processed by JSC archivists to determine the image subject category, e.g., Earth observation, with each image assigned a unique NASA identification number.

Imagery taken by cosmonauts is typically entered into the NASA system after receipt from the Rocket Space Corporation Energia, contractor to the Russian Space Agency. Once received on the ground and processed, the imagery is delivered to the CEO group – or historically, to a precursor group – for cataloging and entry into an online database, the Gateway to Astronaut Photography of Earth (http://eol.jsc.nasa.gov). If the imagery was downlinked in a raw camera format, it is converted into a full-resolution JPEG format for public access through the database in order to reduce server and network loads; the raw camera files (if available) can be requested through JSC Media Services.

The image cataloging process begins with determination of the image centerpoint coordinates. In contrast to data collected by current automated orbital sensors, there is no geolocation data embedded in astronaut photographs – recall that off-the-shelf cameras are used. The time of image acquisition, if accurate, can be used with the known orbital position of the spacecraft (e.g., the ISS) to determine a nadir-viewing ground coordinate useful as an initial estimate of the image's centerpoint coordinates. This estimate typically needs refinement however due to the unconstrained nature of handheld astronaut photography – all viewing angles, from essentially nadir to highly oblique, are available within the constraints of the spacecraft window, and the image centerpoint may be some distance from the spacecraft nadir point. This lack of standard viewing angles requires manual determination of the image centerpoint geographic coordinates by analysts using other georeferenced data – such as Landsat scenes or cartographic maps – with a typical location error of 0.1° in latitude and longitude.

Once the centerpoint is determined, descriptive metadata is generated for the image that includes major visible features or landmarks, estimated cloud cover, and the calculated viewing angle/direction relative to the orbital position of the spacecraft. Together with the camera file metadata for each frame (digital camera data only), the image is added to the Gateway to Astronaut Photography of Earth database. While all received ISS and Space Shuttle Earth observations imagery is currently entered into the database, it is prioritized for purposes of cataloging.

The entire digital collection of astronaut photography (more than one million images) is accessible using both map- and metadata-based search tools, and imagery can be downloaded at various resolutions free of charge. Keyhole Markup Language (kml) files for cataloged data also can be generated on the fly for direct input into geospatial browsers such as Google Earth. Digital images that have not been cataloged may also be queried using spacecraft nadir ground location coordinates, times of data acquisition, and lens focal length. Selected astronaut photographs and descriptive content are also available as part of the NASA content layer in the free geospatial browser Google Earth (http://earth.google.com).

Platforms

Manned spacecraft launched by the USA, Russia/former USSR, and other countries have uniformly employed asynchronous inclined elliptical orbits around the Earth. This is due to the relative ease of establishing and maintaining this type of orbit (e.g., less fuel needed to attain orbit and perform attitude adjustments), minimization of loss-of-signal periods for radio communication, and accessibility to landing sites on both land and at sea (Green and Lopez 2009). While this type of orbit limits the degree of nadir-viewing land and sea surface that can be observed to the degree of inclination, it also provides for a wider range of illumination and viewing conditions than typically available for sensors on sun-synchronous, polar-orbiting platforms. NASA retired the remaining Space Shuttles from service in 2011, leaving the International Space Station as the only platform for regular handheld Earth observations for at least the coming decade. While China has announced plans to complete construction of a crewed space station in low earth orbit by 2020, any plans to include collection of handheld Earth imagery as a formal component of science activities are unknown.

International Space Station (ISS)

Originally conceived as the US Space Station Freedom, the ISS orbital inclination was initially chosen at 28° to facilitate launching from NASA Kennedy Space Center in Florida. With expansion of the program to include international partners the inclination was increased to 51.6° to accommodate the Russian launch site at Baikonur Cosmodrome (Eppler and Runco 2001). This inclination allows the ISS to overfly the temperate and tropical regions of the Earth – covering approximately 75% of the Earth's land area and approximately 95% of the Earth's population (Fig. 28.1). The ISS orbit varies in altitude from approximately 350–455 km asl; due to atmospheric drag, reboosting of the ISS to maximum altitude is required approximately every 90 days. Due to the westward precession of orbit tracks, the ISS has an approximate repeat time over the same location every 3 days, with similar lighting conditions being repeated every 3 months not correcting for seasonal lighting shifts. For purposes of Earth observation, the CEO team generally limits daily target selections to regions with at least a 20° sun angle (elevation above local horizon) in order to have adequate illumination of ground targets. This constraint combined with ISS orbit precession and seasonal precession of the Earth's orbit around the Sun also produces intervals when only Northern or Southern Hemisphere ground targets meet the illumination criteria (Fig. 28.1). This constraint does not hold for atmospheric or nighttime ground targets.

The (ISS) Destiny Laboratory Window

The US Destiny Laboratory Module of the ISS has a window port built into its nadir facing side (NASA 2006). The window consists of three panes of Corning 7940 fused silica which are approximately 56 cm in diameter, providing an approximately 51 cm clear aperture. The ISS program agreed to upgrade the glass in the Destiny window to a set of stringent optical performance requirements in 1996.

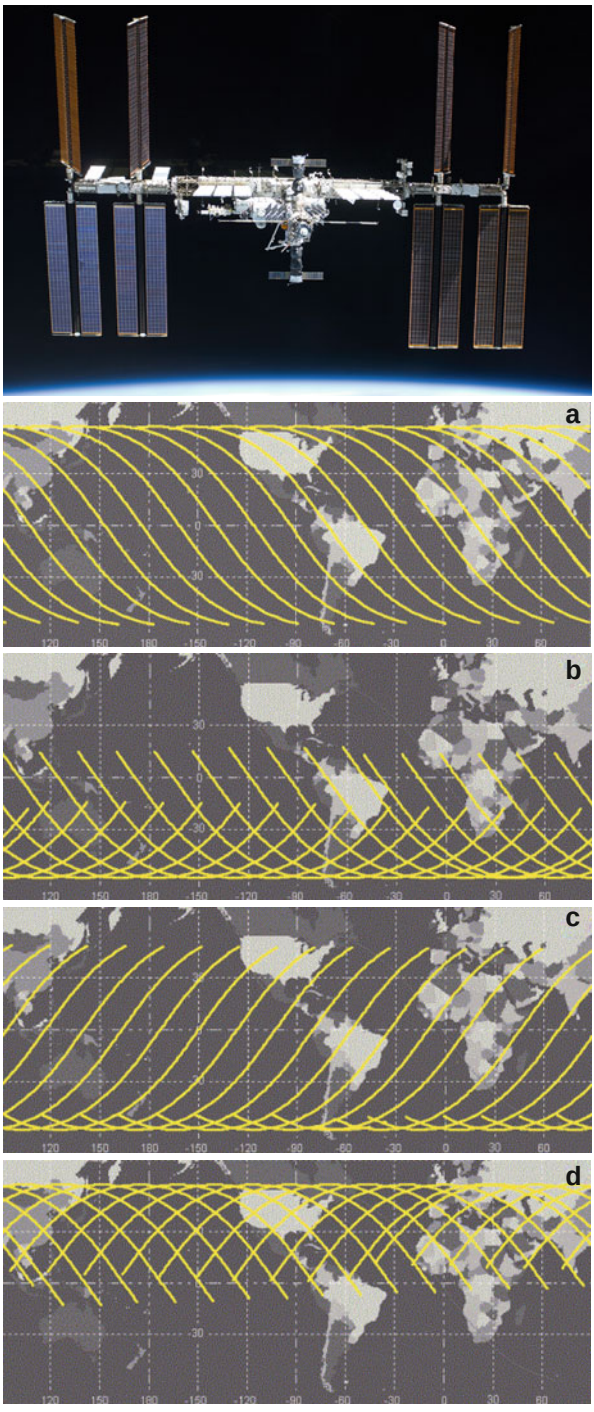

Fig. 28.1 International Space Station as viewed from Space Shuttle Atlantis during the STS-132 mission (Image S132-E-13221, taken 23 May 2010). Westward orbit ground track precession for the ISS at left. (**a**) Successive descending orbit tracks, daylight illumination in both North and South Hemispheres; (**b**) Daylight illumination in South Hemisphere only; (**c**) Ascending orbit tracks, daylight illumination in both North and South Hemispheres; (**d**) Daylight illumination in North Hemisphere only

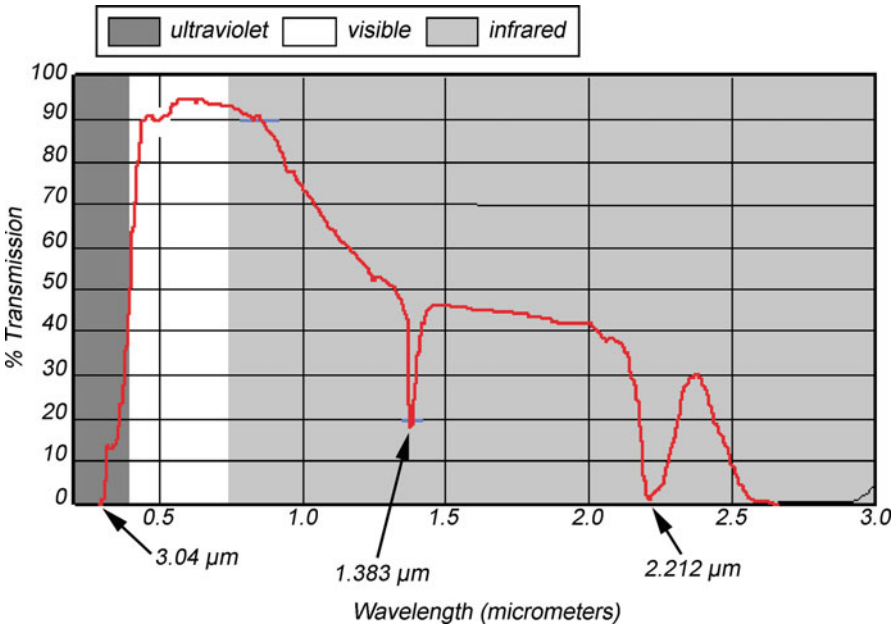

Fig. 28.2 Transmission curve for the center of the as-flown Destiny laboratory window. Cutoff below 0.304 μm is caused by a reflective coating

The Destiny window has a wavefront error of λ/15 peak-to-valley over a 15.2 cm aperture relative to a reference wavelength of 0.6328 μm, which allows the use of up to a 30 cm telescope with no degradation of wavefront due to the glass. These properties give the Destiny window the highest performance of any window ever flown on a crewed vehicle (Eppler and Runco 2001).

With the support of the ISS program, the flight article window was radiometrically calibrated prior to installation in the Destiny Laboratory in May of 2000. This calibration indicated that the window had better than 95% transmittance in the visible region, with a steep drop-off in the ultraviolet (due to a reflective coating) and a gradual drop-off into the infrared wavelengths (Fig. 28.2). Window transmittance decreases to 50% or less at approximately 1.3 μm.

In addition to the Destiny window, there are a number of other viewing ports on the ISS that are frequently used for Earth observations. Windows in the Russian Service Module (or Zvezda), albeit of lesser optical quality, provide both nadir and oblique viewing opportunities of the Earth. A moveable viewing module, the Cupola (Fig. 28.3), was transported to the ISS in 2010 during the STS-130 mission of Space Shuttle Endeavour and attached to the Tranquility Module. The Cupola includes seven optical-quality fused silica and borosilicate glass windows that provide 360° viewing capability, and was designed to support vehicle docking, remote manipulator arm operations, and Earth and space observations (European Space Agency 2011).

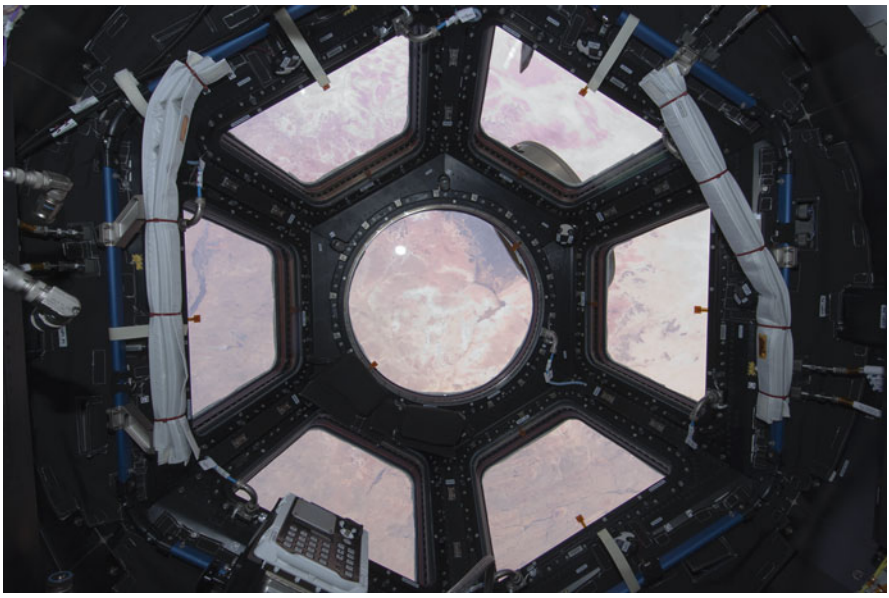

Fig. 28.3 Astronaut photograph ISS022-E-66972 of the Sahara Desert as seen through the cupola onboard the ISS (Image acquired 17 February 2010)

Window Observational Research Facility (WORF)

Complete utilization of the optical performance of the Destiny window would be impossible without a facility to allow stable positioning of research payloads in the window. Design and fabrication of the Window Observational Research Facility, or WORF, began in 1998. The WORF facility was transported to the ISS aboard the Space Shuttle Discovery in 2010 during the STS-131 mission.

The WORF is based on an ISS-standard Express rack (NASA 2006) to capitalize on the Express philosophy in accommodating sub-rack payloads. The WORF is essentially an Express rack with an approximate cubic meter-sized space in the middle (Fig. 28.4), centered on the Destiny window. This space – the payload volume – provides mounting surfaces for window payload hardware, including mounting on a stiff lower payload shelf that is designed to minimize transmission of ISS vehicle vibrations into the optical components of the payload. The interior of the WORF is sealed by means of an aisle-side hatch. The interior of the payload volume is painted flat black to minimize stray light and allow investigations of faint upper atmosphere phenomena such as aurora and noctilucent clouds.

The WORF can provide power, data, and cooling water for up to three payloads simultaneously by interfacing with existing ISS systems. At present, the WORF can provide an average downlink data rate on the order of 2 Mbps, although this may be improved with proposed communications infrastructure improvements to ISS. Investigators can operate their payloads autonomously at their institution, with up- and downlink data going through the Huntsville Operations Support Center at

Fig. 28.4 The Window Observational Research Facility (WORF) installed over the US Destiny Laboratory module window onboard the ISS. The Destiny window is visible through the WORF payload volume at image center (Image S131-E-8619 was taken 10 April 2010)

Marshall Space Flight Center in Huntsville, AL. The general design philosophy of WORF favors autonomous payloads, but crewmembers can operate payloads from the Destiny laboratory aisle using an externally mounted laptop computer.

It is an axiom in the US manned space program that a trained crewmember is one of the best analytical tools Earth observations can employ. The WORF is designed to accommodate crew stabilization devices and brackets to allow vibration-free operation of still cameras and video recorders. In addition, the aisle side hatch allows crew members to interface with a piece of equipment dubbed the "kayak shroud," which allows access to the interior of the WORF without glare from the Destiny Laboratory aisle interfering with Earth photography.

Remote Sensing Using Astronaut Photography

Advantages and Limitations

The most significant distinction of astronaut photography as a research dataset is the most obvious one – these images are framed and acquired by a human being rather than an automated sensor system. The astronaut can make on-the-fly decisions about image targets (e.g., pointing), resolution of data collected (through selection of cameras lenses), and whether conditions are favorable for taking

imagery (e.g., acceptable illumination and cloud cover) that are beyond the capabilities of automated sensor systems. A full orbit of the earth takes approximately 90 min, during which time the ISS crosses both illuminated and dark portions of the globe. The astronaut photograph dataset contains great variability in illumination conditions, look angle, spatial resolution (typically 4–40 m/pixel), and repeat imagery of a given location on the earth's surface.

The majority of astronaut photographs of the Earth have been acquired using film and digital cameras sensitive to the visible blue, green, and red wavelengths of the electromagnetic spectrum (0.38–0.72 μm), with specific experiments conducted using filters and film sensitive to narrow bandpasses within this range and in the near-infrared wavelengths (~0.72–1.30 μm; see ▶ Chap. 26, "Introduction and History of Space Remote Sensing" – for discussion of the historical development of remote sensing).

The use of off-the-shelf digital SLR cameras is somewhat limiting for quantitative spectral analysis of digital astronaut photography due to the generally broad bandpasses of the visible blue, green, and red channels, particularly in images taken with moderate to low illumination (Fig. 28.5). Without application of wavelength-limiting filters, these broad bandpasses make application of traditional spectral analysis and classification techniques difficult due to potential contamination of spectral information from adjacent channels. High- to medium-resolution digital astronaut photographs however contain significant spatial information content as recorded by pixel-to-pixel brightness variations, and this information can be capitalized on using sophisticated classification techniques such as object-based image analysis (OBIA).

Object-based image analysis uses image segmentation to identify homogeneous image objects at several different scales, rather than the classical pixel-based (and single-scale) classification approaches. Membership of pixels in a given image object is determined by rule-based analysis using fuzzy classification algorithms incorporating spectral character, shape, and neighborhood relationships across the class levels (Baatz et al. 2008; Blaschke et al. 2004). The application of OBIA to high-resolution digital astronaut photographs was explored for land cover classification of both urban and coastal ecosystems, and found to perform comparably to classifications derived from orbital multispectral data (Stefanov and Vande Castle 2006).

Astronaut photography presents challenges with regard to preprocessing and quantitative analysis, but these challenges are not insurmountable with currently available image-processing software. Variable look angles, acquisition times, and resolutions inherent to the astronaut photography dataset makes it a highly useful addition to more traditional sources of remotely sensed data, particularly for time-series analysis and change detection (Gebelein and Eppler 2006; Robinson et al. 2002; Stefanov et al. 2003). Most recently, astronaut photography from the ISS supported investigations of atmospheric phenomena such as aurora and polar mesospheric (or noctilucent) clouds; sea ice transport and plankton blooms; and snow cover during the International Polar Year of 2007–2008 (Evans et al. 2006). The following examples illustrate applications of astronaut photography to

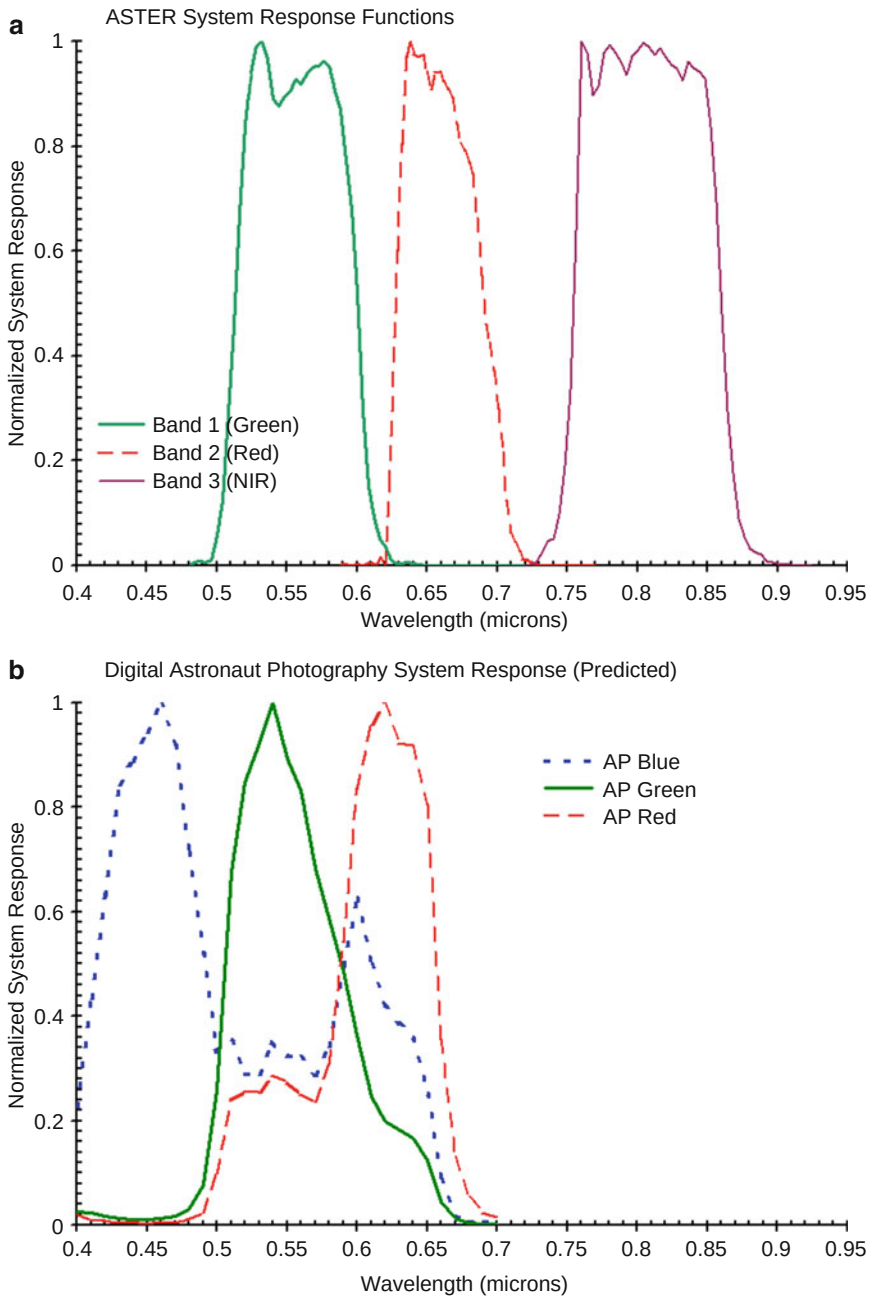

Fig. 28.5 Normalized system response curves for the visible *blue*, *green*, and *red* bands of the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) sensor (**a**) and predicted response for Kodak DCS 760 camera flown on the ISS (**b**). Note the overlap below 0.6 system response between *blue*, *green*, and *red curves* for the Kodak camera

geomorphic mapping, urban ecology, and volcano monitoring and response. These examples are intended to convey a sense of the potential of astronaut photography for Earth remote sensing, and are by no means all-inclusive.

Mapping of Megafans ("Inland Deltas")

Astronaut imagery has made an unexpected contribution to the study of world landscapes. It revealed the existence of numerous *megafans*, also known (inaccurately) as inland deltas, hundreds of km in radius, in many parts of the world, where only a few had been reported in local regional geological literature (Fig. 28.6). Because megafans are dramatic in their size – up to 650 km in radius, with a 200,000 km^2 area for the largest – there had been several claims in the literature for the "largest fan" on the planet. The global astronaut view suggested that a systematic global survey was needed, especially since claims for the largest fan *excluded* the largest that had actually been described.

By showing unknown examples of these features in various parts of the world, handheld imagery provoked a wider systematic search, which proved productive scientifically. Combined with other imagery, the global view revealed the significance of large fans. First, large fans can be claimed to be a significant landform because it is widespread (Hartley et al. 2010). Prior regional studies had shown the existence of a few of these large features. Low local numbers perhaps lulled geologists and geomorphologists into thinking these features were merely the insignificant tail end of the alluvial fan population (*alluvial fans* are fan-shaped cones of sediment that accumulate at the foot of mountains, being very common in the American Southwest, with small radii, usually <25 km [Blair and McPherson 1994]). Cataloging modern megafans worldwide showed their presence on all continents, with >160 very large fans (radii >100 km: Wilkinson et al. 2010) now known between 55°N and 55°S. Megafans can be so large that they constitute major features on many continental surfaces, especially when nested – there are an estimated 1.2 million km^2 in South America alone. The significance of this landform is suggested by the fact that almost every flat zone (with areas >100,000 km^2) on the continents is occupied by megafans (Wilkinson et al. 2011). We show an example from the roughness map of the eastern Sahara Desert and plains of central South America (Fig. 28.7).

Several aspects of this "find" in the astronaut imagery dataset are intriguing. Geologists and geomorphologists had assumed they knew the broad makeup of continental surfaces fairly well, especially in terms of major features, and especially in cloud-free more desertic zones where remotely sensed imagery had promoted familiarity with the landscapes. But geologists and geomorphologists were not *expecting* to see these features, and therefore did not see them – or at least did not accord them any particular significance. The variable perspective and ground resolutions of the astronaut imagery revealed an entire *set* of unforeseen landscapes and landscape relationships. It needed this unusual imagery to clarify what now seems a simple point, that rivers lay down vast quantities of material on continents, far from the oceans. Controls are an erosional zone, a river, and a neighboring basin to accomodate the river sediment. If the basin is wide the fans will be large.

Fig. 28.6 Okavango megafan (*outlined*), northwest Botswana, is one of the most visible and photogenic large fans, with its vegetated fingers radiating from an apex, where the Okavango River (a highly reflective section appears in sunglint above the apex in this northwest-looking view) spreads laterally (*arrows*). The radius of this fan is 140 km. This is a well-known visual cue to astronauts circling over southern Africa (NASA image STS043-151-32 was acquired on 8 August 1991)

Research based on the new understanding that megafan formation is a normal midscale component of river behavior on continental surfaces has been published in diverse fields. The megafan model is the basis for a new theory of Amazonian landscape development (Wilkinson et al. 2010), a set of new theories of fish speciation (Wilkinson et al. 2006), and the basis of a fluvial theory of evolution of the Martian surface where rover *Opportunity* has been performing its investigations (Wilkinson et al. 2011).

Future study of astronaut imagery is likely to yield other scientifically important finds, because it has the potential to show us new features and processes on the Earth's surface. Also, the human brain "behind the lens" can accomplish the critical function of selection, thereby reducing the amount of imagery to be processed. A new view, even of the multiscale oblique kind, can lead to a significant change in what we see. The megafan advance in understanding would not have been predicted.

Urban Geography and Ecology

Large urban areas are easily recognizable from orbit, and cities have been a frequent subject of astronaut photographs since the Gemini program. The rich historical record of city photographs acquired during the Apollo, Skylab, and Shuttle-Mir programs was used by Robinson et al. (2000) to compare urban growth

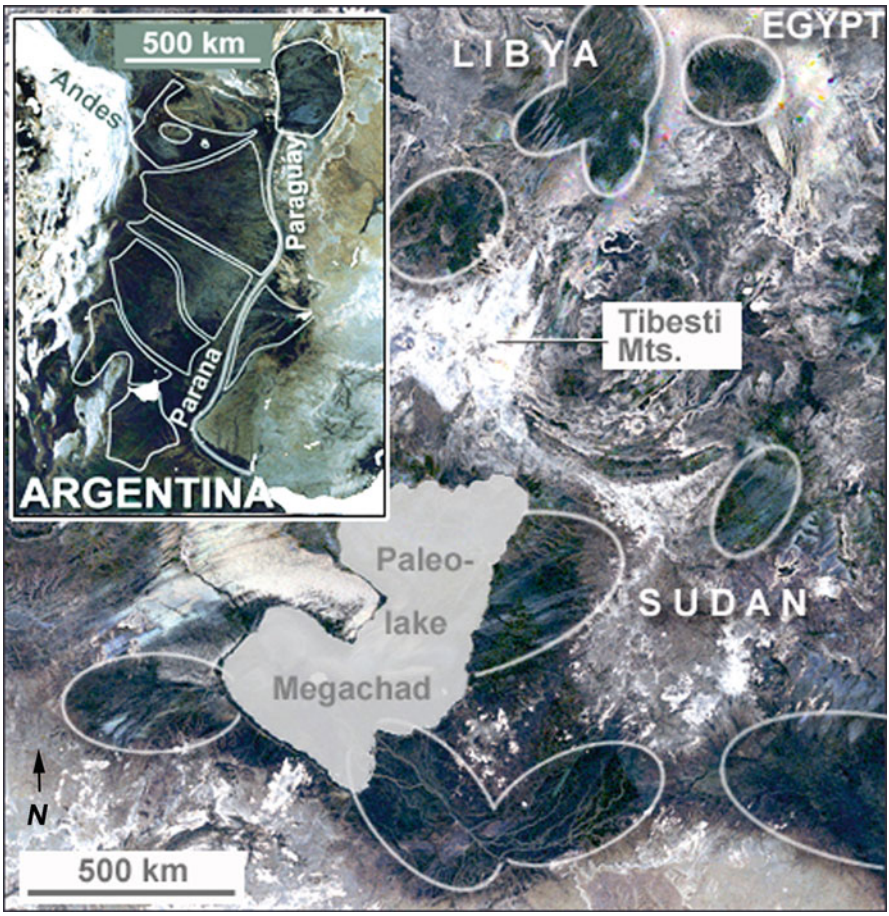

Fig. 28.7 *Darkest tones* in this roughness map of the Eastern Sahara Desert indicate areas of low slope, smooth topography covering very wide areas (note *scale bars*). All are surfaces formed by nested megafans (*outlined*). The inset figure is a similar map for the extensive plains of central Argentina and Paraguay provided for comparison. Rougher surfaces such as mountains and dune fields are light-toned

patterns and rates with population change for six North American metropolitan areas (Vancouver, Chicago, San Francisco, Dallas/Fort Worth, Las Vegas, and Mexico City). Photographs spanning a 28-year period were digitized, co-registered, and resampled to uniform pixel size to enable mapping of urban areal extent and measurement of change (Fig. 28.8). The results of the study provided insight into the variability of rates of urban land cover expansion relative to urban population growth in large North American metropolitan areas during 1969–1999. The first 2 years of this period predate publically available multispectral data from automated orbital sensors and highlight the temporal extent of the astronaut photography dataset.

Fig. 28.8 Change in Mexico City urban extent from 1969 (*inner gold polygon*) to 1996 (*outer red polygon*) – a 112.3% increase in built-up area. The Mexico City metropolitan area experienced less increase of built area relative to population growth over this time period compared to other North American cities examined by Robinson et al. (2000). Base image NM22-741-54B was acquired in December 1996

The transition from film to digital cameras during the first decade of the twenty-first century facilitated the application of digital image processing and analysis techniques to astronaut photography. A comparison of true-color (RGB) digital camera imagery of the Paris, France metropolitan area, obtained from the ISS, with visible and near-infrared data of similar spatial resolution from the Advanced Spaceborne Thermal Emission and Reflection (ASTER) sensor onboard the Terra satellite (acquired 2 weeks earlier) was performed by

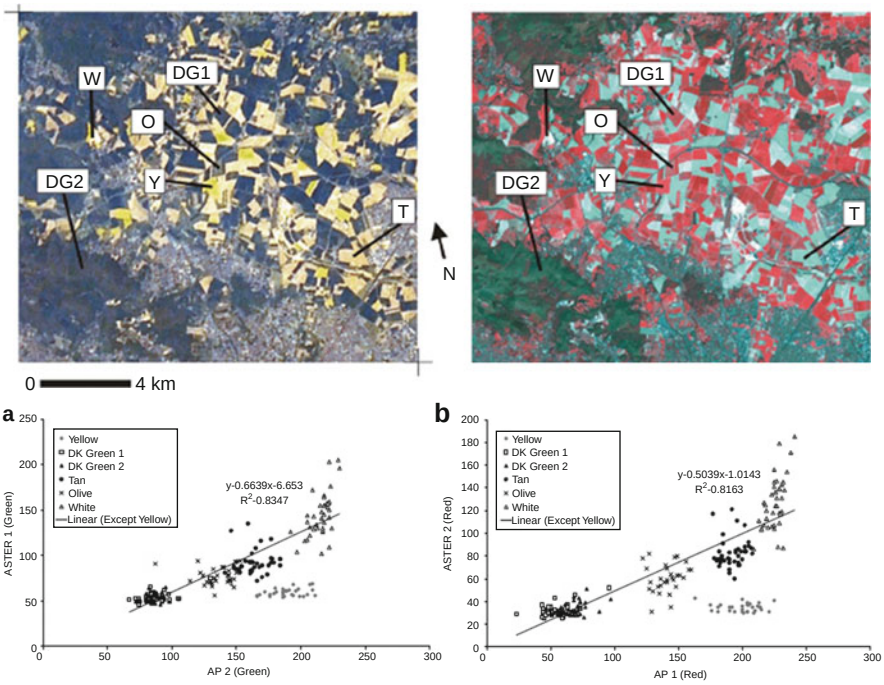

Fig. 28.9 Comparison of visible RGB digital astronaut photograph (AP; *left*) and visible to near-infrared (bands 4, 3, 2 as RGB) ASTER data (*right*) for agricultural fields in the northwestern Paris, France, metropolitan area. Y – *yellow*: vegetation, high productivity; DG1 – *dark green* 1: vegetation, moderate to low productivity; DG2 – non-canopied vegetation; T – *tan*: bare soil; O – *olive* 1: sparsely vegetated soil; W – *white*: light colored soils and built materials. (**a**) green band correlation; (**b**) red band correlation

Stefanov et al. (2003). The primary goal of this study was to identify the nature of yellow agricultural fields observed in the astronaut photograph that had no comparable signature in the ASTER data. Digital number values (DN, representing pixel brightness) recorded by both ASTER and the digital camera (Kodak 760 DCS) in the green and red bands were highly correlated for a number of vegetation and soil classes (Fig. 28.9). While the results of the study indicating that the data from both imagers could be reliably compared, the difference in coloration of the agricultural fields resulted from the flowering of rapeseed (*Brassica* sp.), a common commercial crop in the region. The digital astronaut photograph (image ISS004-E-10414, acquired on 24 April 2002) captured the phenological change of the rapeseed which had not occurred at the time of the ASTER overpass 2 weeks earlier. The study highlights the power of combining temporally variable astronaut photography with the more regularly acquired automated sensor datasets to obtain denser time series for urban ecological and agricultural monitoring purposes.

Volcanic Eruptions and Hazard Monitoring

The inclined equatorial orbit of the ISS allows observation of active volcanoes located within (or near to) approximately 52° North or South latitude at variable times, providing the potential to capture data on eruptive activity outside the repeat frequency of polar-orbiting satellite sensors. Frequent communication between ISS crews, ground controllers, and even the general public through Internet social networking sites also provides a rapid-response capability for potentially hazardous eruptions. This capability was dramatically demonstrated on 23 May 2006, when ISS Expedition 13 Flight Engineer Jeff Williams observed volcanic activity at Cleveland Volcano, located within the Aleutian chain of islands extending westward from Alaska (Fig. 28.10). Eruptions of Aleutian volcanoes can pose hazards to transcontinental airline flights because volcanic ash can disable jet engines. Cleveland Volcano is not heavily instrumented by the United States Geological Survey (USGS), and Williams was the first person to see (and report to the USGS) the eruptive activity from his vantage point in orbit.

The frequently serendipitous location of the ISS within observing distance of erupting volcanoes has also provided unique imagery of value to the volcanological community. The striking astronaut photograph of a pileus cloud forming during the large 2009 eruption of Sarychev Peak Volcano in the Kuril Islands chain is one of the best records of this unusual feature (Fig. 28.11). The pileus cloud was formed by rapid lifting of a moist air mass by the eruption column, and sequence photography of the eruption allows for analysis of the cloud formation and plume dynamics (Lockwood and Hazlett 2010; Venzke et al. 2009).

The value of high-resolution digital astronaut imagery of active volcanoes obtained from the ISS has been recently recognized by NASA, which has funded efforts to include photographs of volcanoes recognized as particularly hazardous, e.g., Mount Merapi in Indonesia, in the ASTER Volcano Archive (http://ava.jpl.nasa.gov). In addition to increasing astronaut situational awareness of active volcanoes and adding new imagery to the Archive, the potential value of fusing high-resolution astronaut photographs with low-resolution thermal infrared data from ASTER is being investigated in order to improve geologic hazard maps and response plans.

Public and Education Outreach Applications

It can be posited that NASA fundamentally changed humanity's perspective of the planet Earth, and our own importance within the cosmos, with an astronaut photograph. That photograph was taken in 1972 during the Apollo 17 mission as the astronauts looked back at the small "blue marble" of Earth, surrounded by the vastness of seemingly empty and dark space, on their way to the Moon. Some historians credit this image, and others like it, as helping to galvanize public opinion that led to important environmental legislation (such as the Clean Air and Water Acts) in the USA during the 1970s (Green and Jackson 2009). The public's fascination with looking at Earth from the vantage point of an astronaut on an orbiting platform continues today on the International Space Station (Fig. 28.12).

Fig. 28.10 Ash plume eruption from Cleveland Volcano on Chuginadak Island in the Aleutian Islands chain as seen from the International Space Station (The image (ISS013-E-24184) was acquired by the Expedition 13 crew on 23 May 2006)

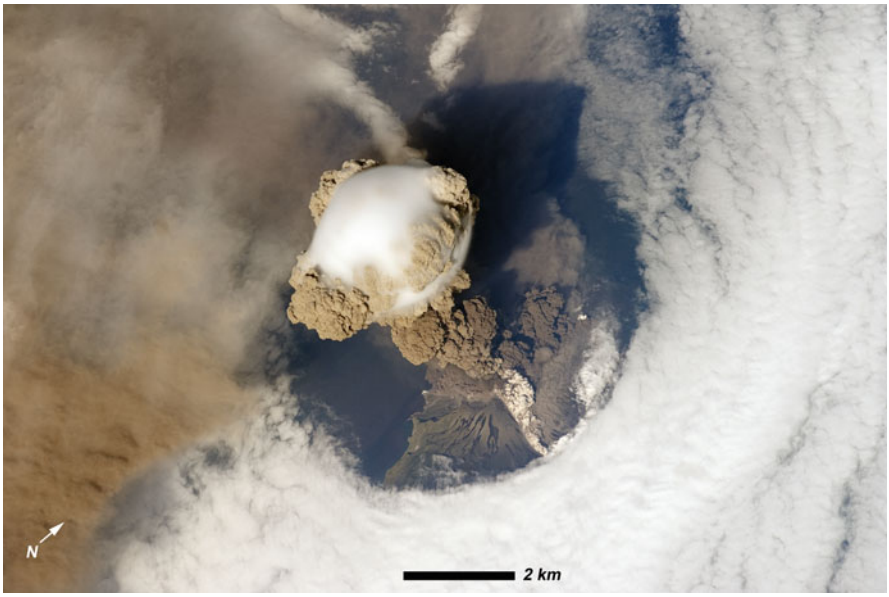

Fig. 28.11 Ash plume eruption, pyroclastic flows, and pileus cloud (image center) from Sarychev Peak Volcano, Matua Island in the Kuril Islands chain as seen from the International Space Station (The image (ISS020-E-9048) was acquired by the Expedition 20 crew on 12 June 2009)

Fig. 28.12 Apollo 17 "blue marble" view of the Earth showing the African and Antarctic continents (Image AS17-148-22727 was taken on 7 December 1972)

Public Outreach

Public access and distribution of handheld imagery of the Earth has evolved in step with the technological advances since the 1960s. Initially, the only way for the public to view astronaut imagery was to travel to the Earth Resources Observation and Science (EROS) Data Center in Sioux Falls, South Dakota, the Earth Data Analysis Center (EDAC) at the University of New Mexico in Albuquerque, or to the Media Service Center at NASA Johnson Space Center in Houston, Texas. With ready access to the Internet, today the global public can view and download astronaut imagery of the Earth through the Gateway to Astronaut Photography of Earth, or GAPE, web site (described above). Public dissemination of astronaut photography now includes social media outlets, including "tweeting" images directly from ISS via the Twitter web site (http://twitter.com/). Several astronauts have shared their unique views of the Earth by tweeting images along with commentary to the general public in near real time, providing a direct connection with humans working and living in space. These same images can also be accessed through the GAPE web site at various resolutions after working through the downlink and database entry procedure described above.

In recent years, the value of enlisting "citizen scientists" to participate in basic data analysis of large datasets has been proven by numerous online projects, such as Stardust@home and Galaxy Zoo (Wiggins and Crowston 2010). A public cataloging module is now in development for addition to the GAPE. This module will take advantage of the public's interest in astronaut images and ready access to geospatial

data (e.g., Google Earth) to provide an opportunity to participate in enhancing the metadata for the astronaut imagery of the Earth. The citizen scientist will be able to review the dataset of existing Earth imagery, select images, and add metadata such as the location of the center point of the image, cloud percentage, and identification of major features.

Education Outreach

Originally eight NASA Teacher Resources Centers (now called Educator Resource Centers – the number has expanded to 11) distributed slides, prints and 12-in. laser disks, of astronaut imagery on request to educators, museums, etc. Astronaut photographs of Earth have also appeared in textbooks, classroom lectures, and teacher workshops because they can easily be blended into existing classroom curricula without requiring sophisticated image processing or understanding of remote sensing – the visible wavelength, true-color imagery is intuitively interpreted by students. NASA Education Specialists from Oklahoma State University-Stillwater created a curriculum notebook based on astronaut handheld photography and satellite imagery to teach remote sensing as a tool for detecting Earth's features and changes. Themed slide sets of Earth phenomena such as weather/clouds and terrestrial impact craters from existing Shuttle imagery were made available to the public and to educators from the Lunar and Planetary Institute in Houston, Texas. In the mid-1990s, the Houston Museum of Natural Science integrated digital astronaut images into an interactive computerized display in the museum where students could direct virtual flyovers of anywhere in the world. As with public outreach, the education outreach applications of astronaut imagery have also evolved over time.

An initial effort to provide online resources for educators was the Earth from Space photograph collection, now incorporated into the GAPE web site. The content and format of the collection was informed by interactions with educators from all over the USA. Specifically, educators wanted searchable and themed imagery (e.g., cities, earth landscapes, hurricanes, and weather) with extensive captioning, including an indication of the north direction on the image. Earth from Space was originally populated with Space Shuttle imagery and is today updated with ISS imagery; there are now over one million Earth images in the collection.

Direct interaction between educators, NASA scientists, and students are facilitated through the accessibility of astronaut photography. The Crew Earth Observation (CEO) group and Teacher From Space Office, in cooperation with the NASA Aerospace Education Services Project-Montana/Nevada, Earth Observing System Education Project, University of Montana, and the Geospatial Research Group, Dept. of Geology, University of Montana developed an educational project called "Lewis and Clark's Travels: The Astronaut View" in 2003. The CEO office worked with the ISS Expedition 7 crew to take images along the 1804 path of Lewis and Clark to commemorate the 200th anniversary of their expedition. The ISS crew actively participated in this historical event, and often drew parallels between the

ISS mission and the Lewis and Clark Expedition. The images, highlighting locations along Lewis and Clark's westward trek to the Pacific coast were used by educators and historians and incorporated into museum displays, educational curriculum, and public web sites across the USA from Philadelphia and Ohio through Montana to Oregon.

Most recently, NASA has funded efforts to engage students in Science, Technology, Engineering and Math (STEM)-related authentic research that uses astronaut photography as the primary dataset. The Expedition Earth and Beyond (EEAB) Project is a student involvement program that allows teachers and their students in grades 5–14 to be actively involved in the process of science. Student-driven, authentic research projects are used to study the Earth and in some cases to be compared to other planetary bodies. Student teams are mentored by scientists at the NASA JSC and in select cases may request new imagery be acquired from the ISS. Information on the EEAB Project is available at http://ares.jsc.nasa.gov/ares/eeab/index.cfm.

Conclusion

Astronauts have taken images of the Earth using handheld cameras from the early days of space travel, and it is likely that they will continue to do so even with the development of ever more capable automated sensor systems. Indeed, the availability of regularly collected, standardized, and publically accessible remotely sensed data of Earth systems from orbital satellite platforms was enabled by early astronaut photography. Collection of handheld imagery of the Earth progressed from the essentially informal activities of USSR and USA astronauts in the 1960s through more formal programs and experiments during the 1970s and 1980s. Beginning in the late 1990s through today, collection of astronaut photography from long-duration orbital missions has enabled the use of this dataset for true time-series monitoring of selected targets as well as contributing to disaster response and management. The digital nature of current astronaut photography facilitates the application of standard image processing and analysis techniques, increases the volume of data acquired, and decreases the lag time between collection of data and availability to the public.

The human decision-making and response element inherent to astronaut photography continues to provide value and relevance within the current paradigm of Earth-observing automated sensors on satellite platforms. The International Space Station platform and the unconstrained pointing capability of handheld cameras allow for the collection of a dataset that is fundamentally different, yet fully complementary, to polar-orbiting sensor data due to the range of illumination conditions, viewing angles, and ground resolutions available. This enables the acquisition of several unique datasets, including high-resolution nighttime imagery of urban areas and detailed imagery of eruption plumes. The ready accessibility of digital astronaut imagery through online databases and collections fosters use by academic, government, and nonprofit organizations for a variety of purposes.

We expect that handheld astronaut photography will continue to integrate with, and complement, further enhancements of remote sensing capability on the International Space Station. As off-the-shelf digital camera technology improves, so do the opportunities for modification and use in orbit to collect new, unique datasets. Addition of high-definition video cameras to the ISS presents the opportunity to capture and target dynamic events such as wildfire plumes, hurricanes, volcanic eruptions, etc. The emerging human spaceflight programs of other nations may choose to develop their own handheld Earth observation programs; if so, the historical and current programs of the USA and USSR/Russia will provide useful models for data collection and dissemination.

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